Issues in Integrated Health Management of Life Support Systems

Gautam Biswas and Eric-Jan Manders
Vanderbilt University

gautam.biswas@vanderbilt.edu; http://www.vuse.vanderbilt.edu/~biswas

David Kortenkamp
NASA Johnson Space Center/Metrica Inc

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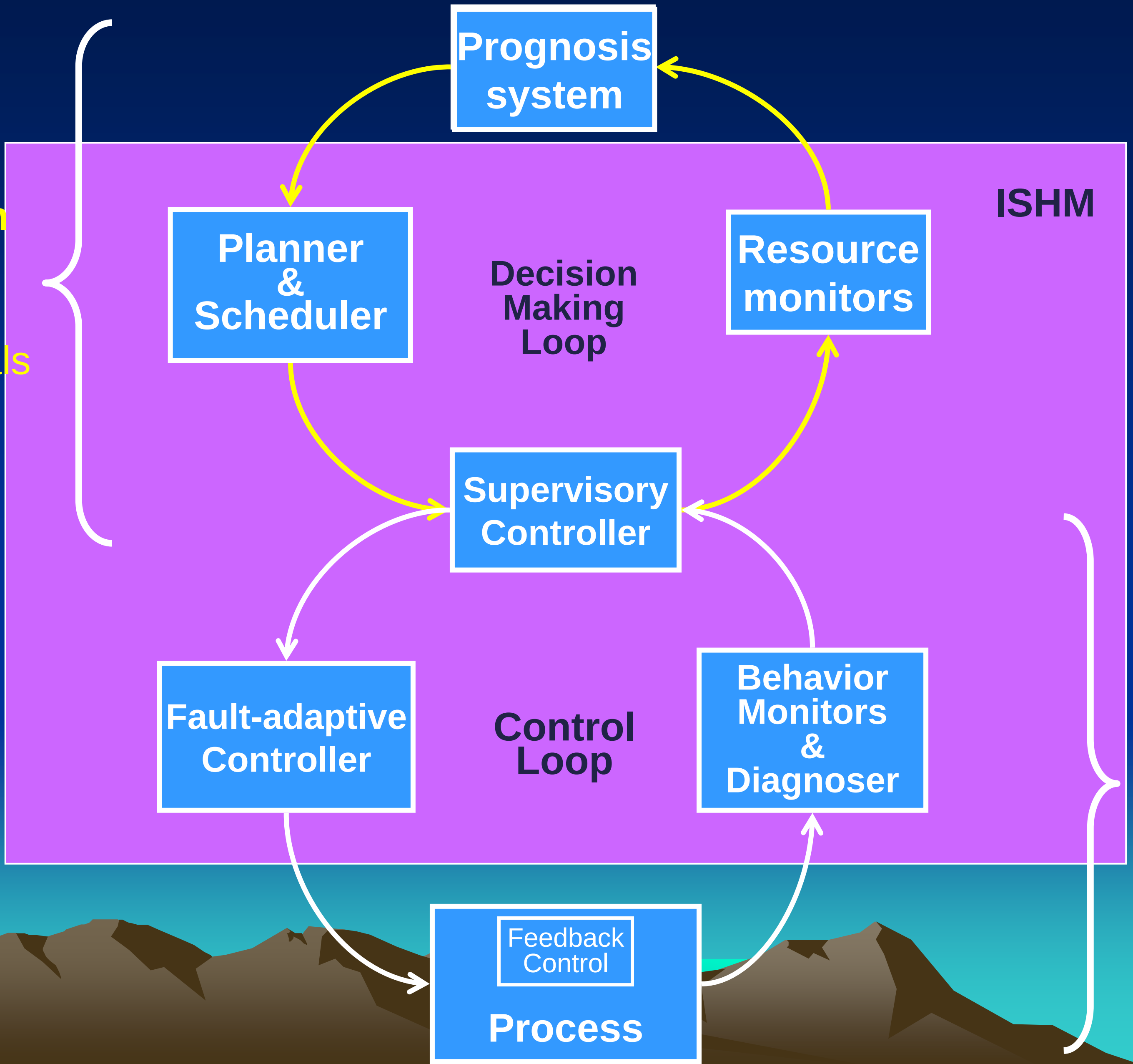
What is ISHM?

- Ability to maintain system safety, health, and performance over the life of the system
- Involves monitoring, control, fault diagnosis, adaptation, reconfiguration and maintenance
- Operates along a continuum of time scales
  - Behaviors (immediate): monitoring and control
  - Performance level (short-term): fault diagnosis, adaptation
  - Health (long-term): mission performance, maintenance, reconfiguration

Issue: What about humans in the loop?

ISHEM Architecture

Long-term issues
(focus on mission goals & needs)



Short-term issues
(keep system safe & operational)

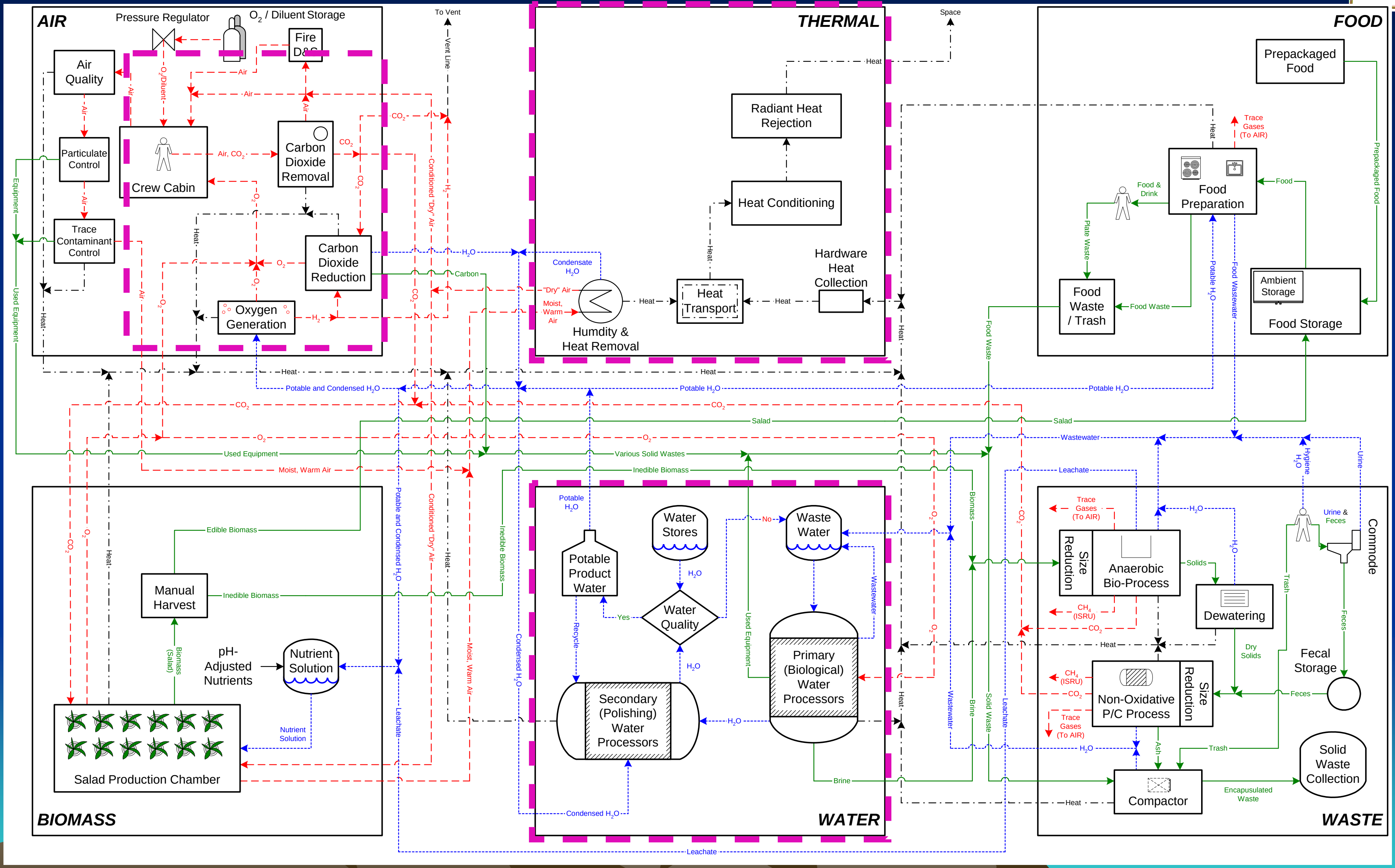
Life support systems

- Life support systems produce consumables for human crew members. Consumables include oxygen, water, and food
- Life support systems process waste products such as carbon dioxide, waste water and solid waste
- Goal: Closed-loop system in terms of material consumption
- Life support systems must be carefully controlled to create a habitable environment
- Faults in life support systems can threaten both the crew and the mission

ISHEM issues for Life Support

- Life support systems pose several unique and significant issues including:
  - *Interacting subsystems*: Life support systems contain many different subsystems that all need to work together
  - *Multiple Time Scales*: The subsystems operate at very different time-scales
  - *Sensing*: The biological components of life support systems make sensing difficult.
  - *Decision-making*: Life support subsystems operate at different time-scales and require decisions both in fast, real-time situations and in slow, long-duration situations
  - *Human involvement*: Humans are a significant part of the life support system in that they produce and consume resources

Surface Habitat -- Architecture



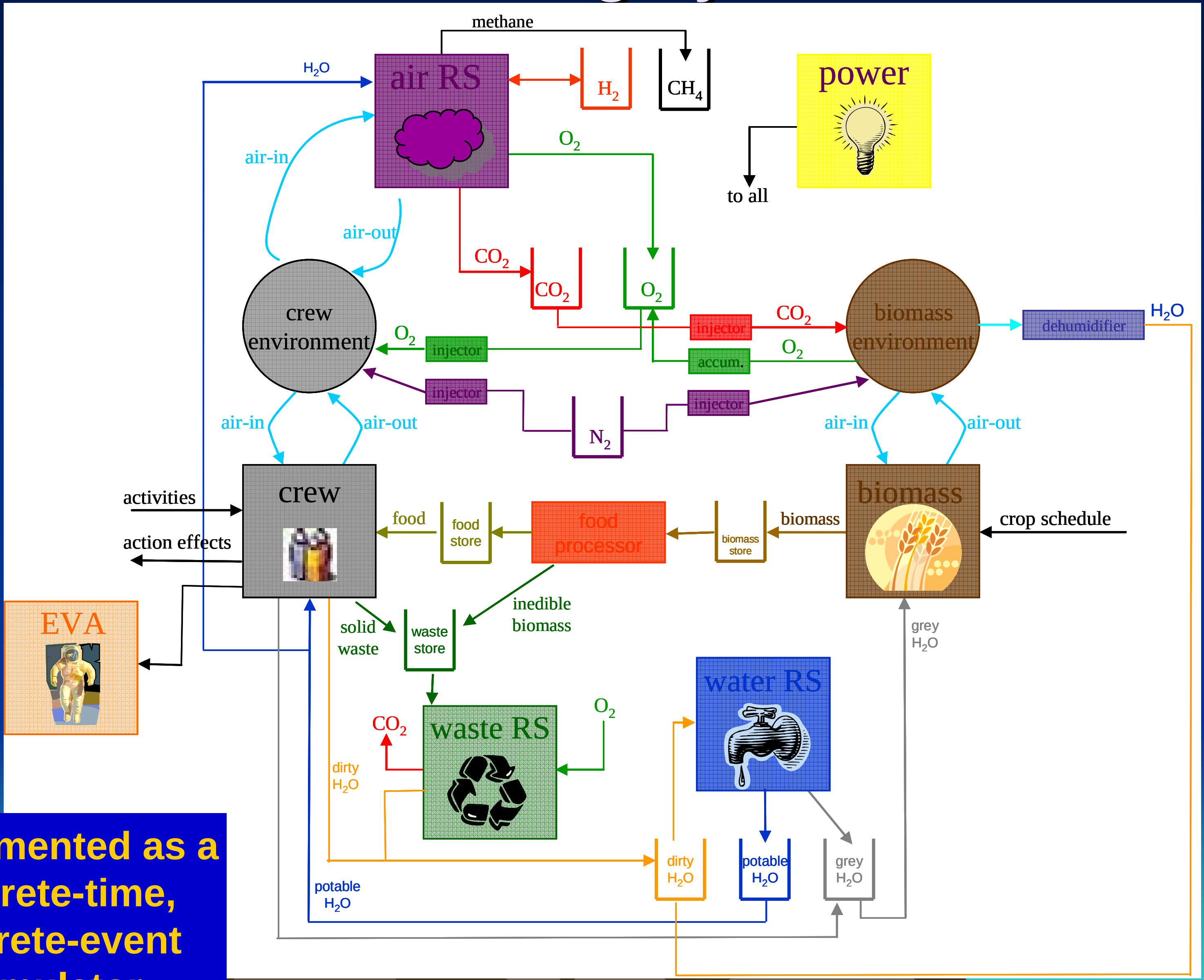
Surface Habitat -- Architecture

Coupled systems

- Crew chamber
- Biomass
- Air
- Water
- Thermal
- Power Generation
- Food
- Waste

Operate at widely differering time constants

Interacting systems



Implemented as a discrete-time, discrete-event simulator Biosim

ISHEM Architecture

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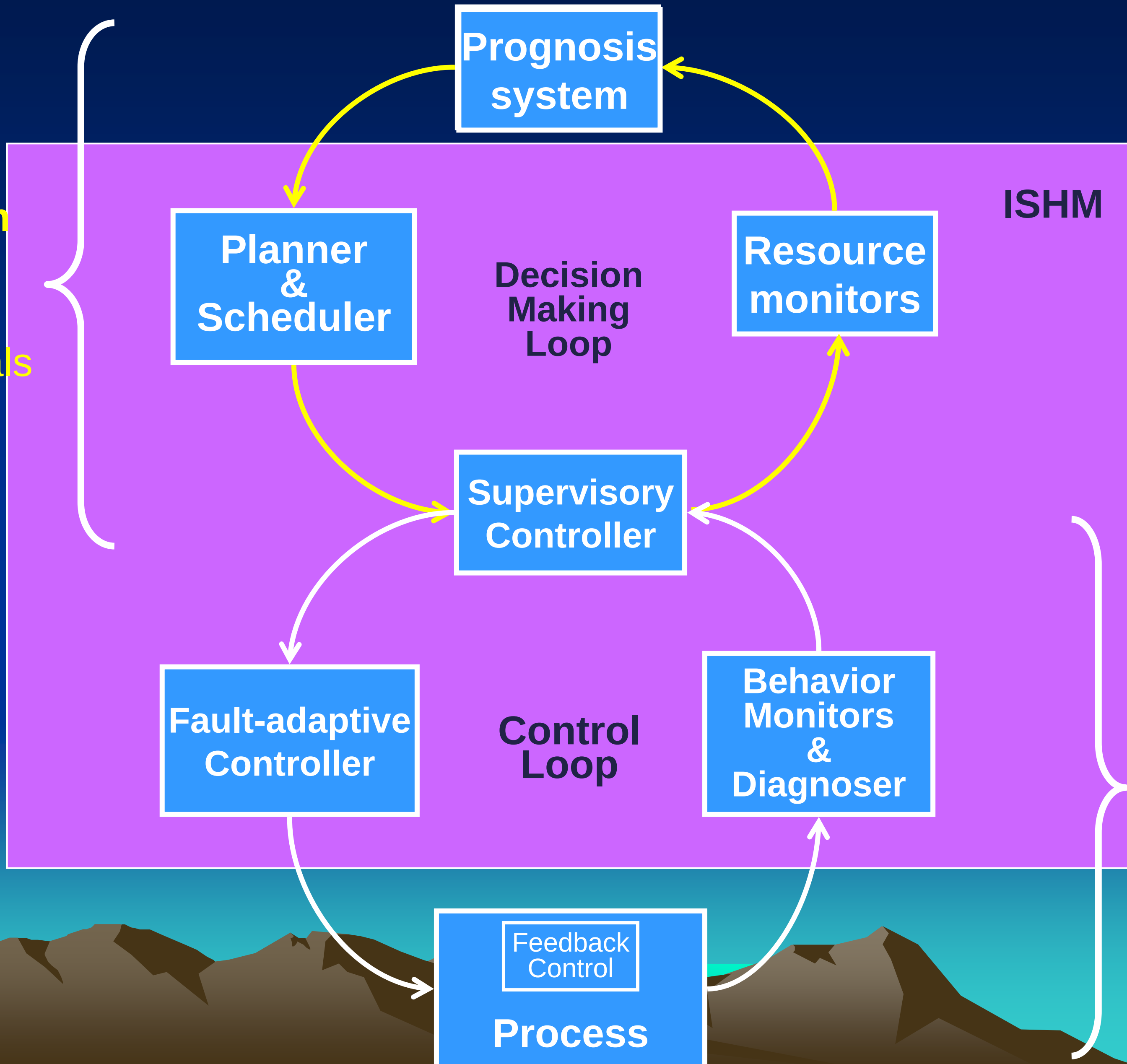

Short-term issues
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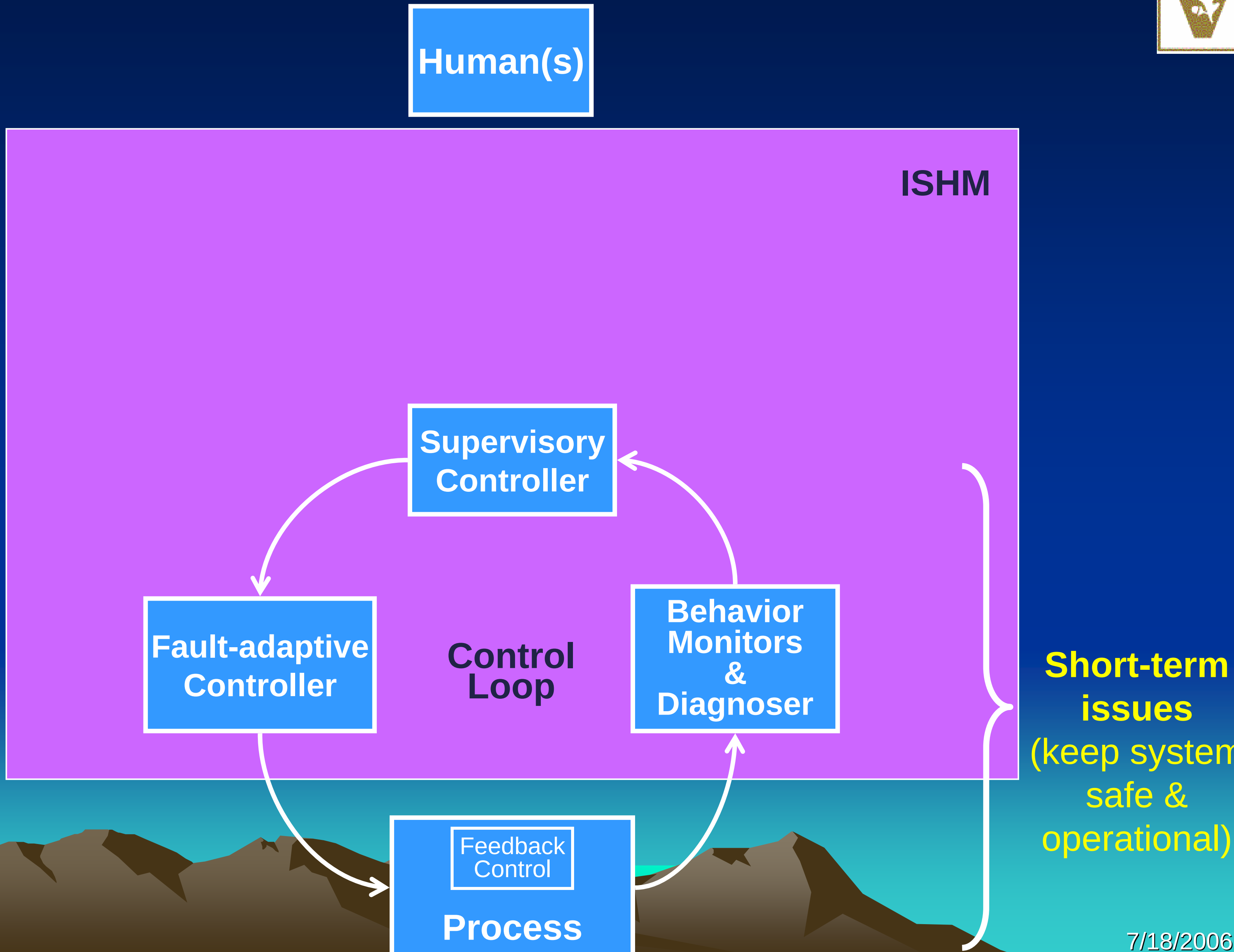
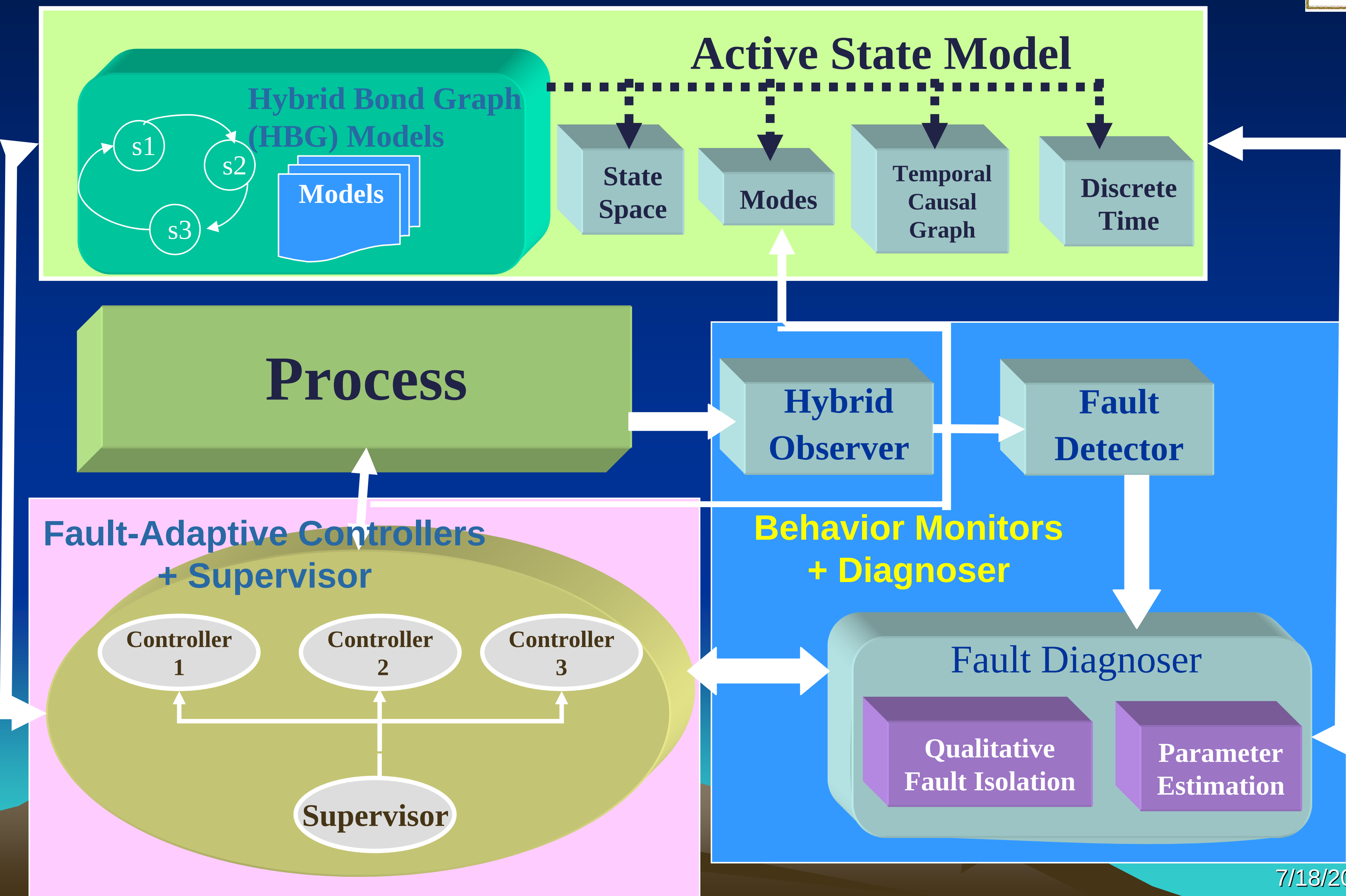
Focus: Short-Term Issues



Fault adaptive controllers Self-Managing Systems

- **Definition**
  - Systems that can manage their resources efficiently to achieve their objectives in a dynamic environment and under varying operation requirements
- **Advantages**
  - Rapid adaptation to dynamic operating conditions
  - Autonomy
  - Automatic recovery from certain class of failures
- **Application Domain**
  - Space exploration systems
  - Manufacturing, Avionics and Automation systems

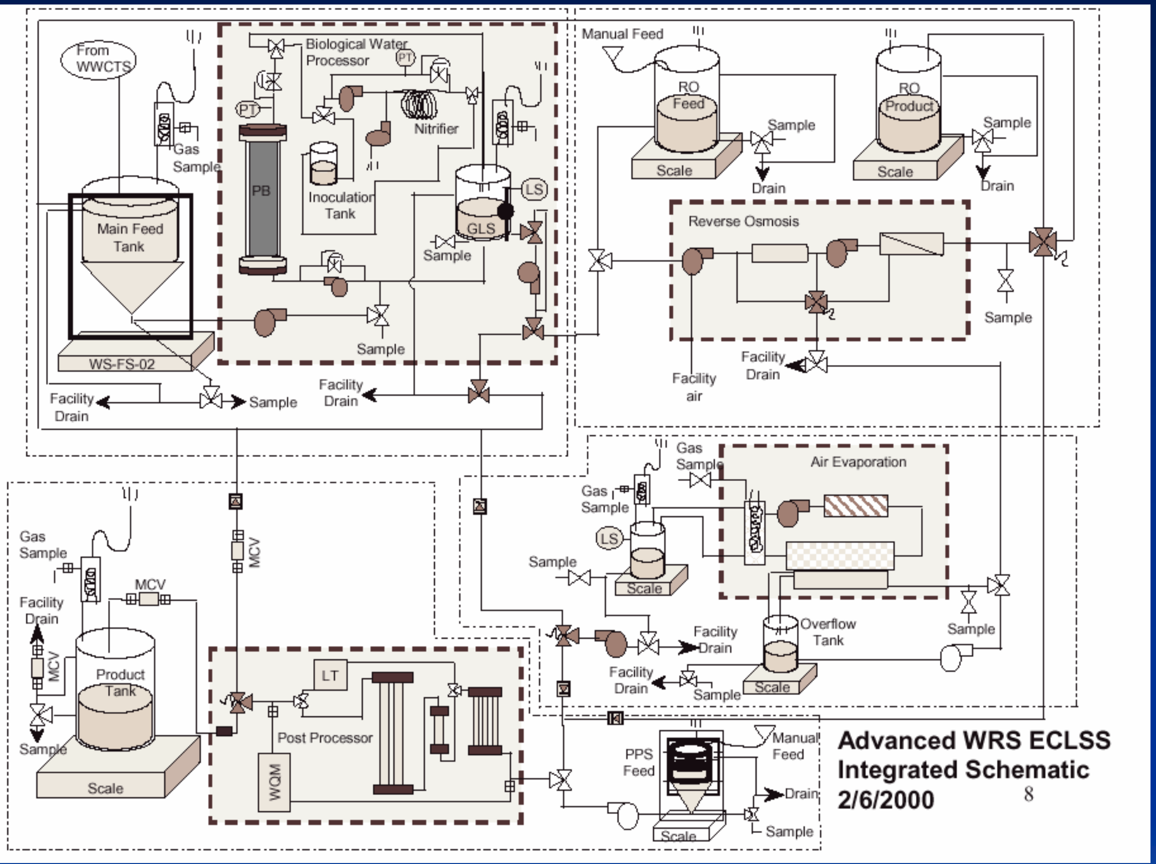
Fault-Adaptive Control Architecture



Modeling Approach

- Integrated Modeling Paradigm
  - Graphical Component-oriented Modeling (GME) → Physics-based models → Models tailored for specific applications
    - Physics-based models: Hybrid Bond Graphs (nonlinearities, switching junctions); Block Diagrams
    - Simulink/Stateflow Models – Energy and mass balance; crew schedule
    - Discrete-time models – Online supervisory control
  - Modeled: WRS, ARS, Habitat, Crew Activity, Power Generation, EVA Activity

Water Recovery System



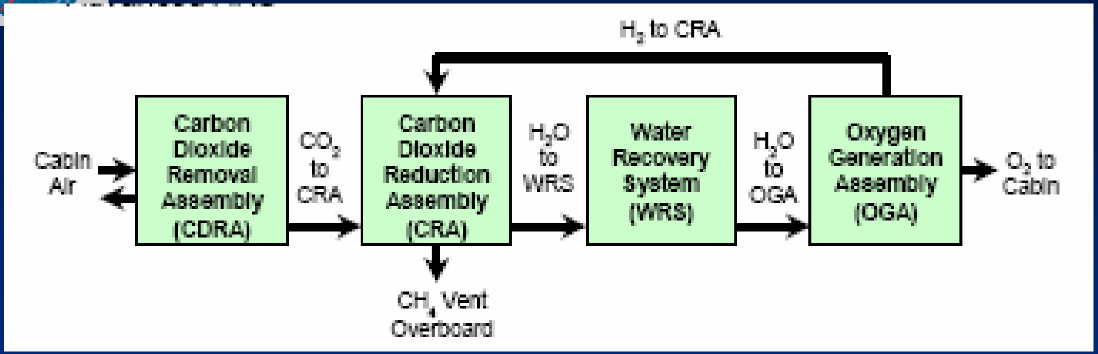
Three subsystems

- Biological Waste Processor (BWP)
  - dirty water circulates in loop through packed bed + nitrifier tubes
  - cleaner organic contaminant-free water collects in GLS
  - control – two pumps + nitrifier cleaning
- Reverse Osmosis (RO)
  - Membrane-based particulate inorganic waste removal
  - water circulates in loop – four modes of operation: primary, secondary, purge, and clean
  - clean water to PPS (not modeled), purged water to AES
- Air Evaporation System (AES)
  - evaporates water from wick, heat exchanger cools down to retrieve pure water

Two storage units:
(1) Waste Water Tank: capacity = 25 liters
(2) Potable Water Tank: capacity = 650 liters
Processing rate: 25 – 50 liters per day
Power Consumption (nominal): BWP = 0.7kW, RO = 0.8 kW; AES = 1.2 kW

Control: Two levels
(1) Local controllers for BWP, RO, and AES
(1) System Controller: WRS

Air Revitalization System

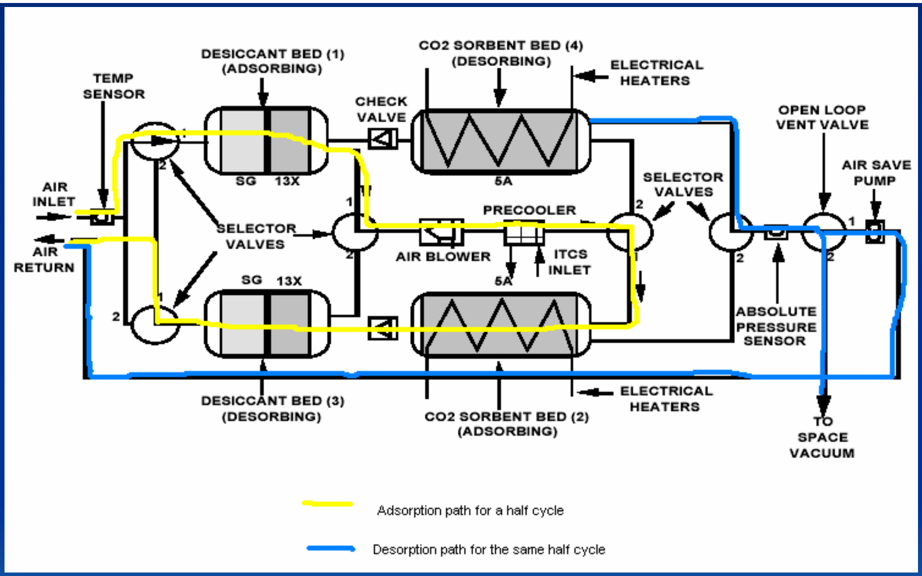


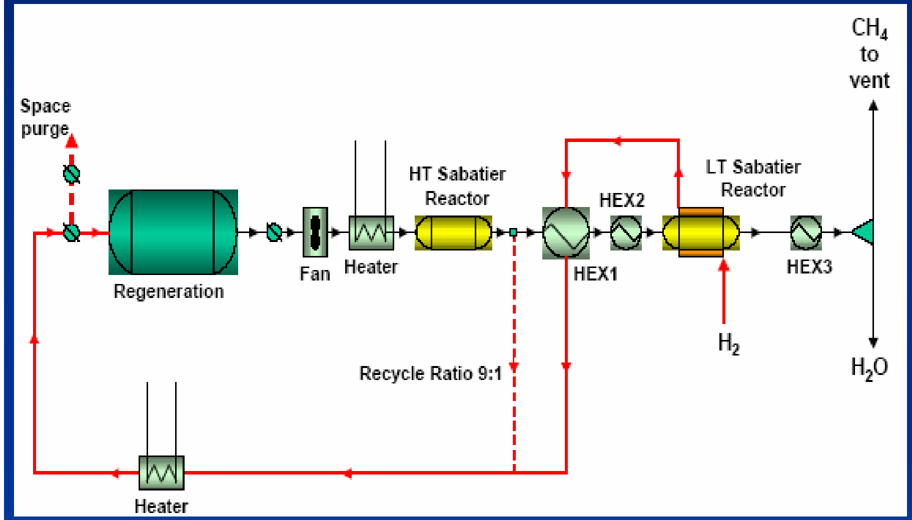
Three subsystems:

(1) CDRA – CO_2 removal

(2) CRS – CO_2 reduction,

(3) OGS -- electrolysis of water into H_2 and O_2





Details: CDRA in tight loop with crew chamber: removes CO_2; O_2 added to restore air quality

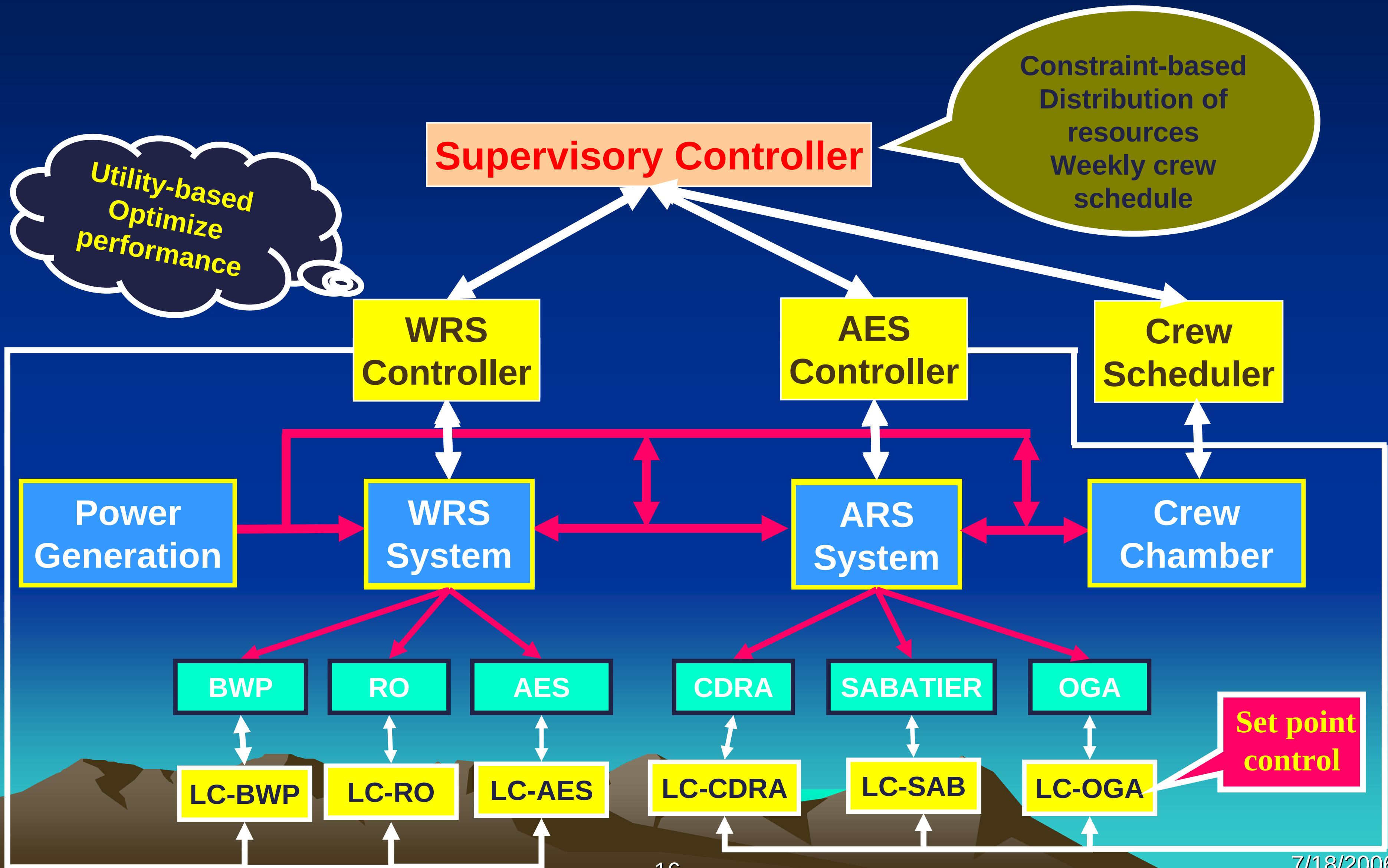
Air flow: between 5 and 10 kg./hour; Cabin air = 25°C

CRS: CO_2 + H_2 in: CH_4 (vented) + H_20 produced (back to dirty water tank); Temp = 425°C processes 0.16 to 0.23 kg of C per hour when on (operates only during the day)

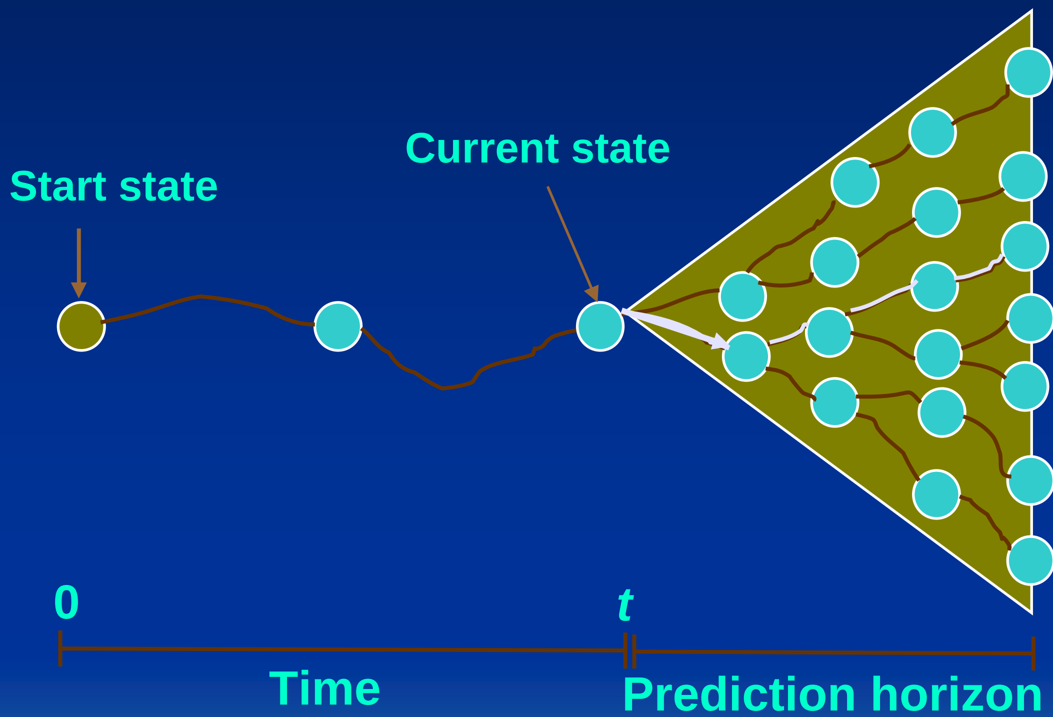
Buffers: (1) CO_2: 4 kg (2) H_2: 0.8 kg (3) O_2: 10 kg (N_2 storage not dealt with explicitly)

Power consumed: CDRA: 0.8 kW; CRS: 0.55 kW; OGS: 0.67 kW.

Hierarchical Control



Utility-based Limited Look Ahead Control



- Use behavioral model to estimate future system states over the prediction horizon
- Obtain the sequence of control inputs that optimize desired utility function
- Apply the first control input in the sequence at time *t*; discard the rest
- Repeat the process at each time step

Online Control Design

- Discrete time model of plant + transitions
- To choose best action, perform look ahead search up to *L* steps
- Define utility function

$$U_i = c_K \bullet \frac{K}{K_{\max}} + c_f \bullet \frac{f}{f_{\max}} + c_{ns} \bullet ns + c_p . \frac{p}{p_{\max}}$$

$$U_T = \sum_{i=1}^{L} U_i$$

$$Choose\ \ action\ \ a_j\ on\ top\ level\ of\ \ tree, such\ that$$

$$U_{a_j \ldots} = \max_P \{U_T\}$$

- Repeat for next time step – accommodates for faults and disturbances in system

SIMA Challenge Problem

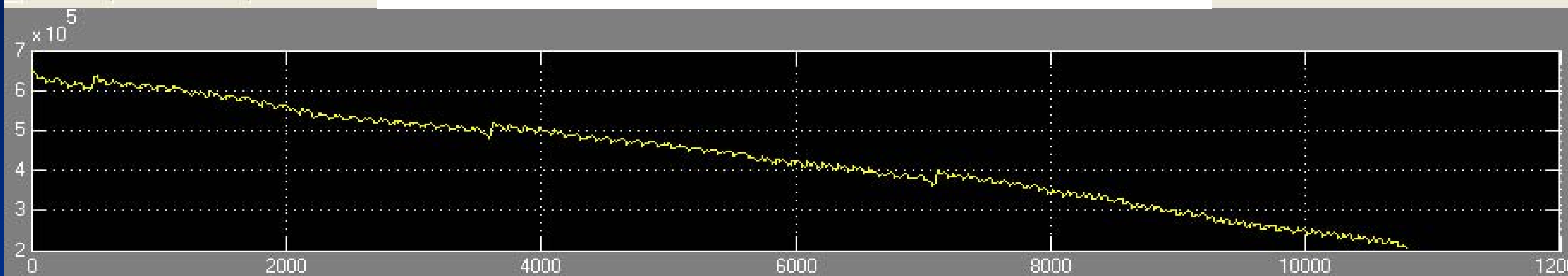
- 90 day surface Habitat Lander of Lunar South Pole (14 day + 14 night cycle)
- One time use of surface habitat
- Crew of four
- Our focus: Air, Water, Thermal, Crew Chamber, Power Generation and Consumption
- Deal with flexible crew schedules

Control Goals: For appropriate size of buffers maintain cabin O_2 and CO_2 levels + temperature
& provide adequate clean water supply at specified levels to support crew habitat + EVA activities
Ensure closed loop operation (minimum waste) of resources while not exceeding power (energy) requirements

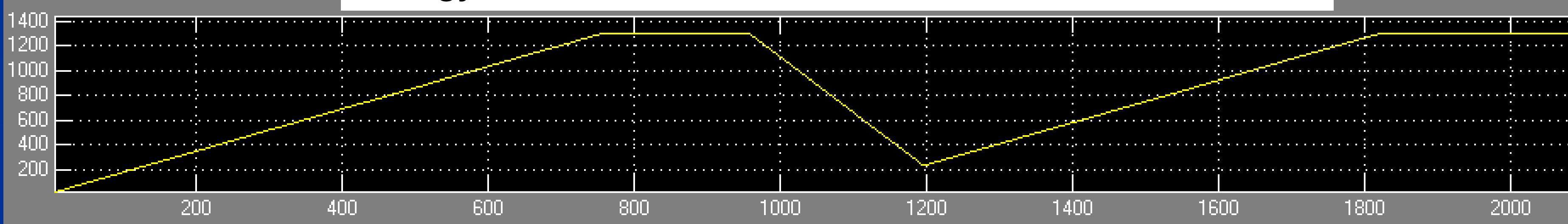
Details: Lunar Reference Mission Document (Hanford and Ewert)

Evaluating System Performance 90 Day Mission

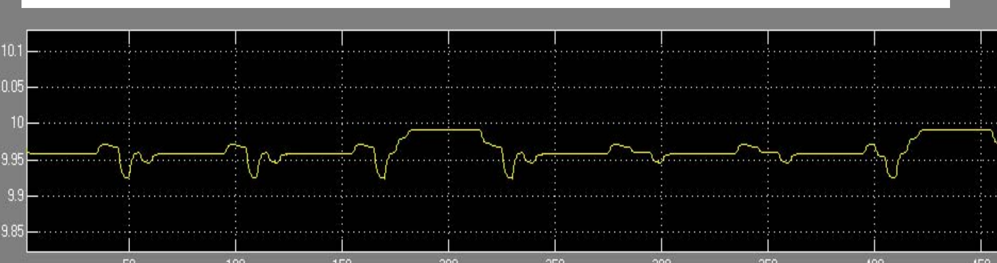
Potable water: Initial: 650 liters; End: 200 liters



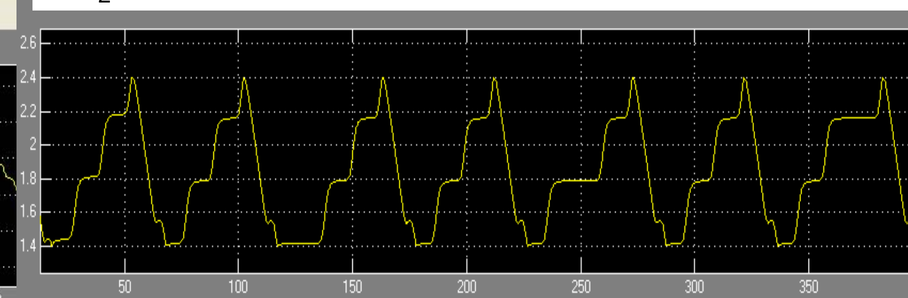
Energy stored: Min: 200 kW-hour; Max: 1300 kW-hour



Oxygen tank: Initial = 9.9 kg; Max = 10 kg; Min = 9.9 kg



CO_2 tank: Initial = 0 kg; Max = 2.6 kg; Min = 1.4 kg

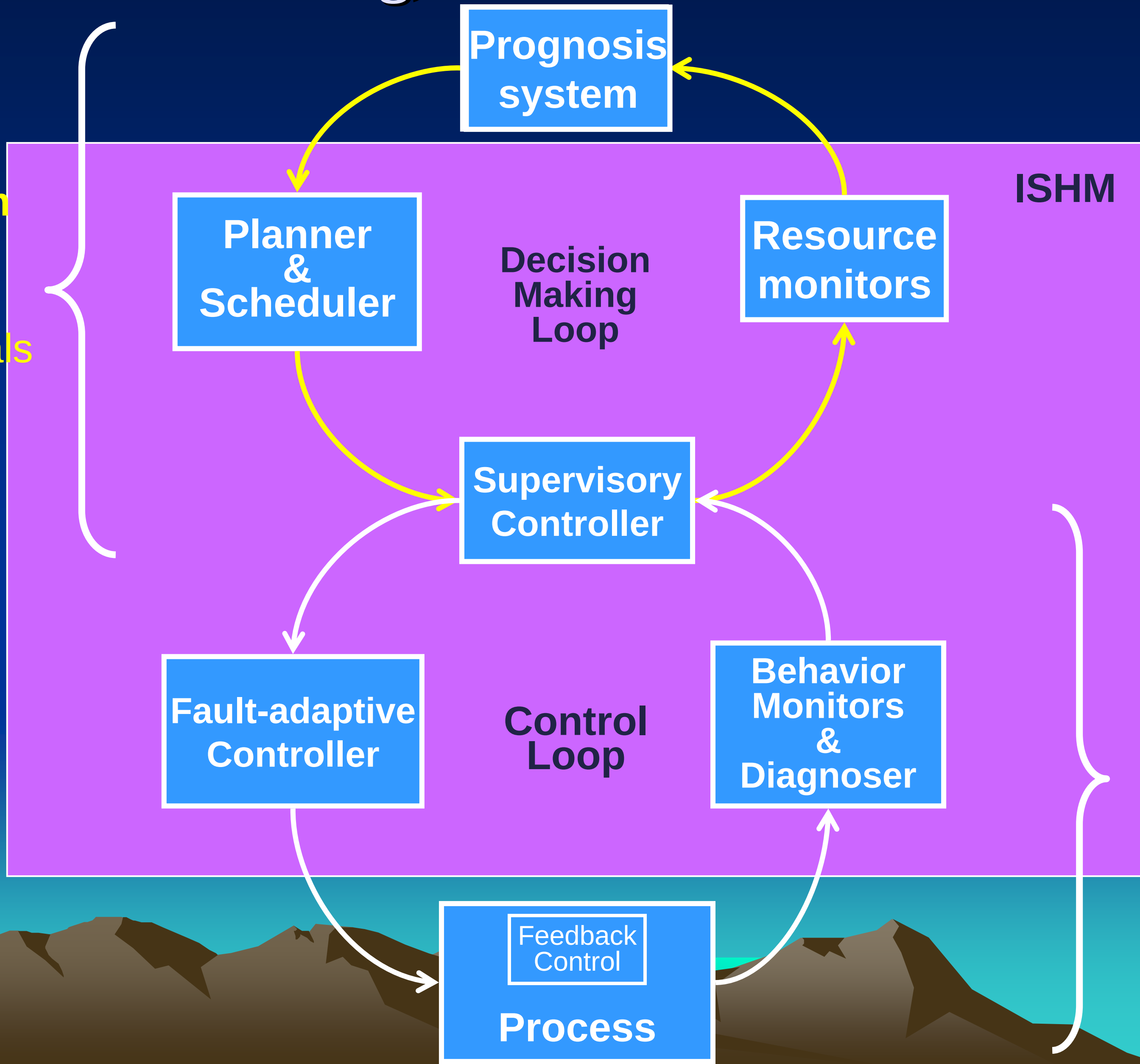


Evaluating System Performance 90 Day Mission

Dynamic modeling allowed robust controller design
But key finding: System required much smaller buffers
Overall reduced Equivalent System Mass (ESM)

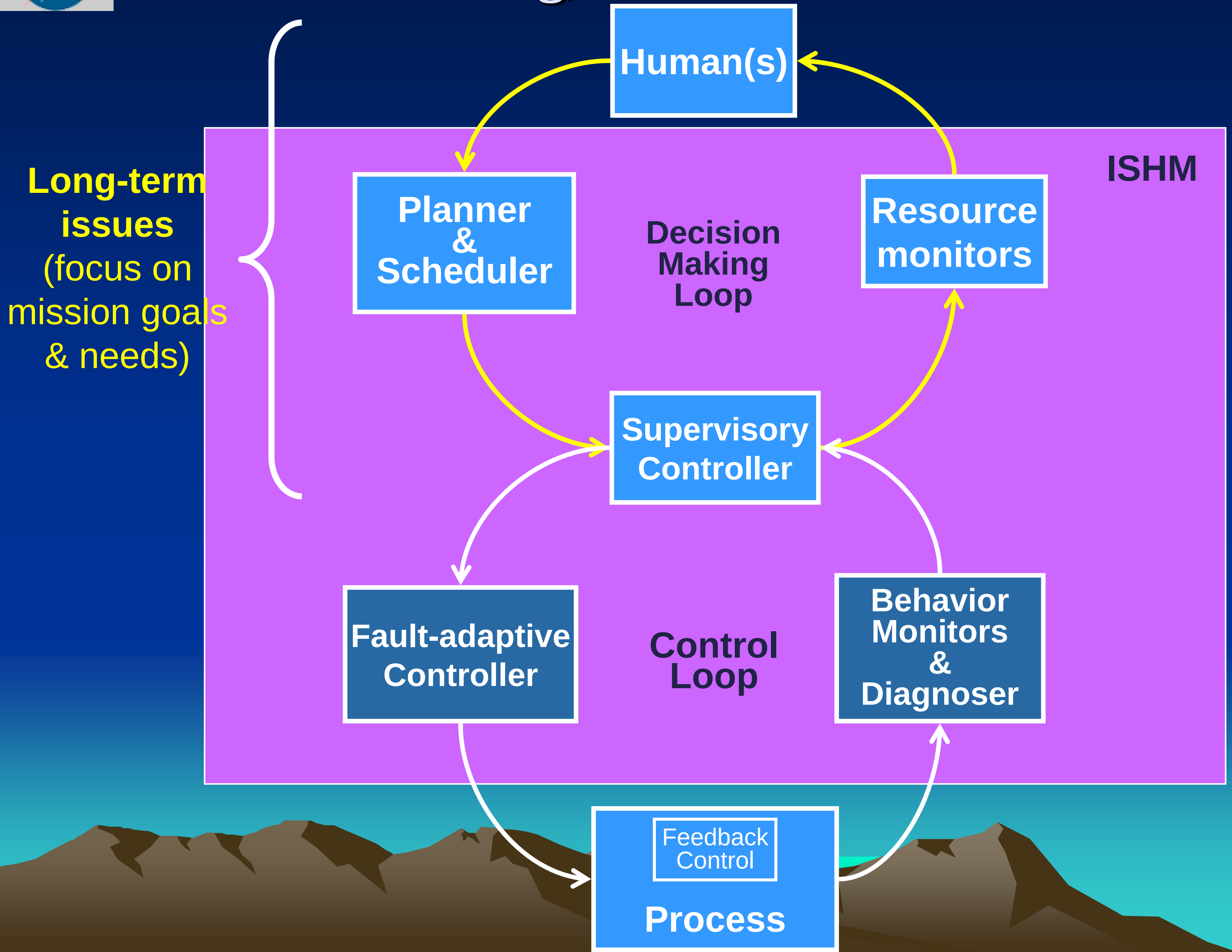
Long-term Issues
Planning, Maintenance & Control

Long-term issues
(focus on mission goals & needs)



Short-term issues
(keep system safe & operational)

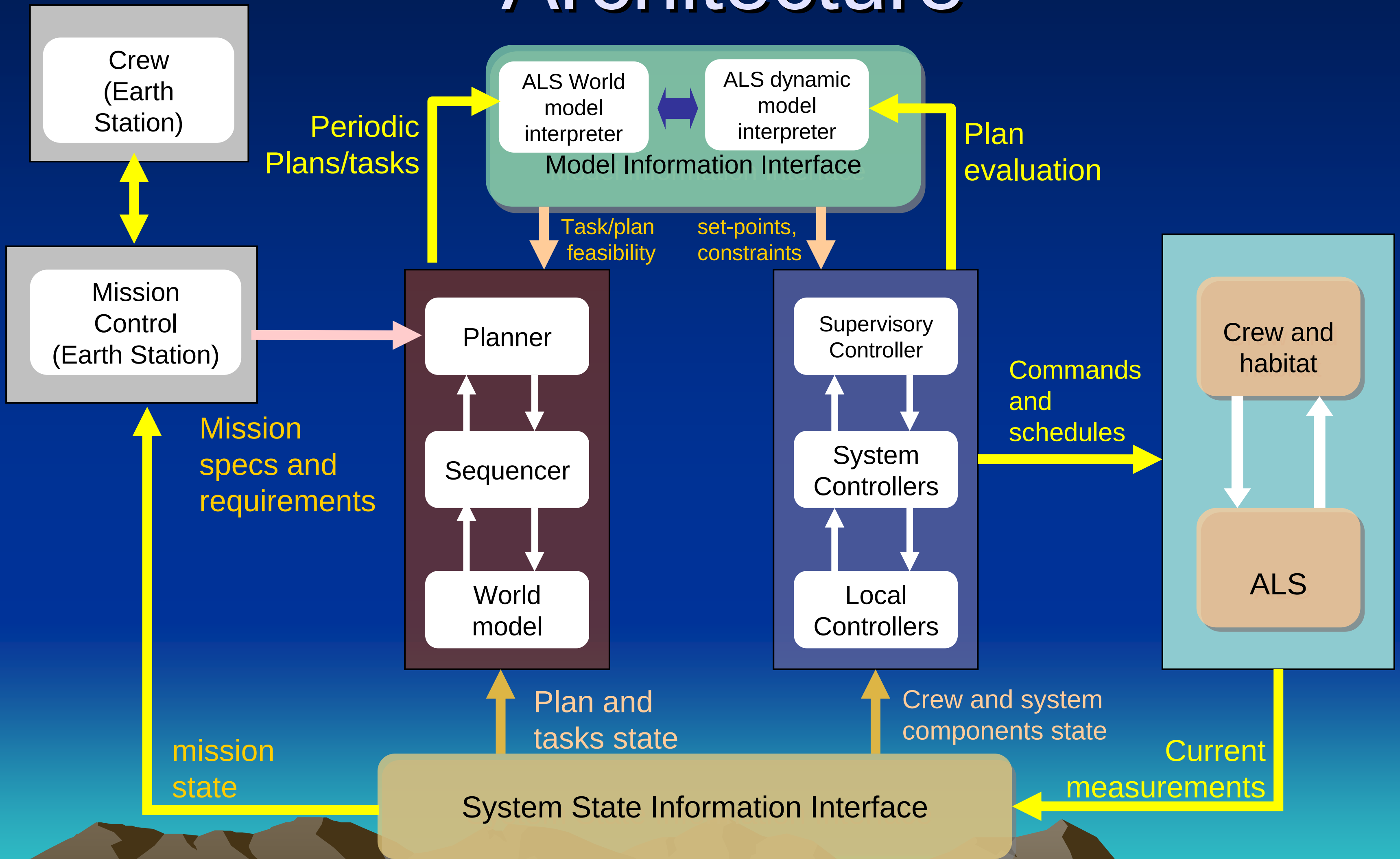
Long-term Issues
Planning, Maintenance & Control



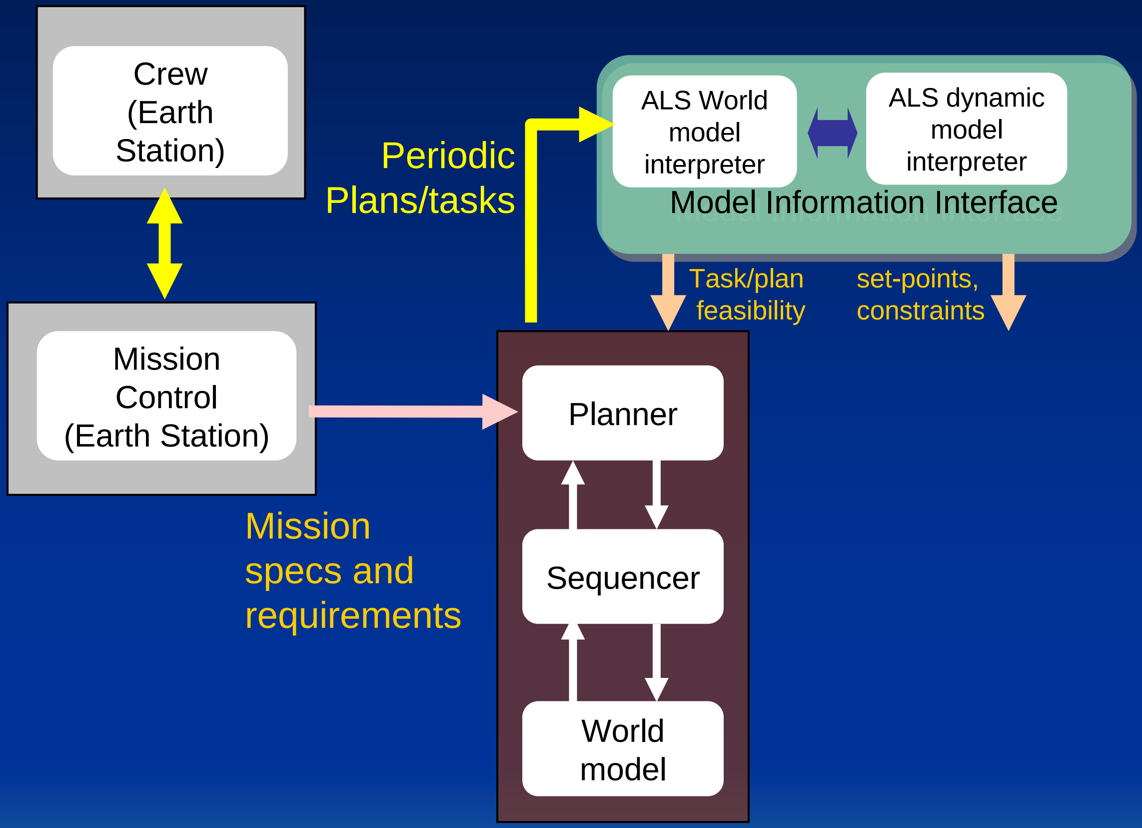
Resource monitors

- From Behavior (and Function) to Performance Monitoring
  - Examples: Monitor power consumption, rate of generation of product
  - Typically, these changes will be small and subtle & accumulate over time
  - Key issue: how to project consequences of subtle (small) changes on behavior, then long-term performance and resources available for mission
- Need ability to monitor + predict, i.e., Prognosis
- ISHM extends resource monitoring + prognosis to decision making
    - Decision making implies actions to correct anomalies, e.g., maintenance, repair, reconfiguration
    - With and/or without humans in the loop

Integrated Planning & Control Architecture

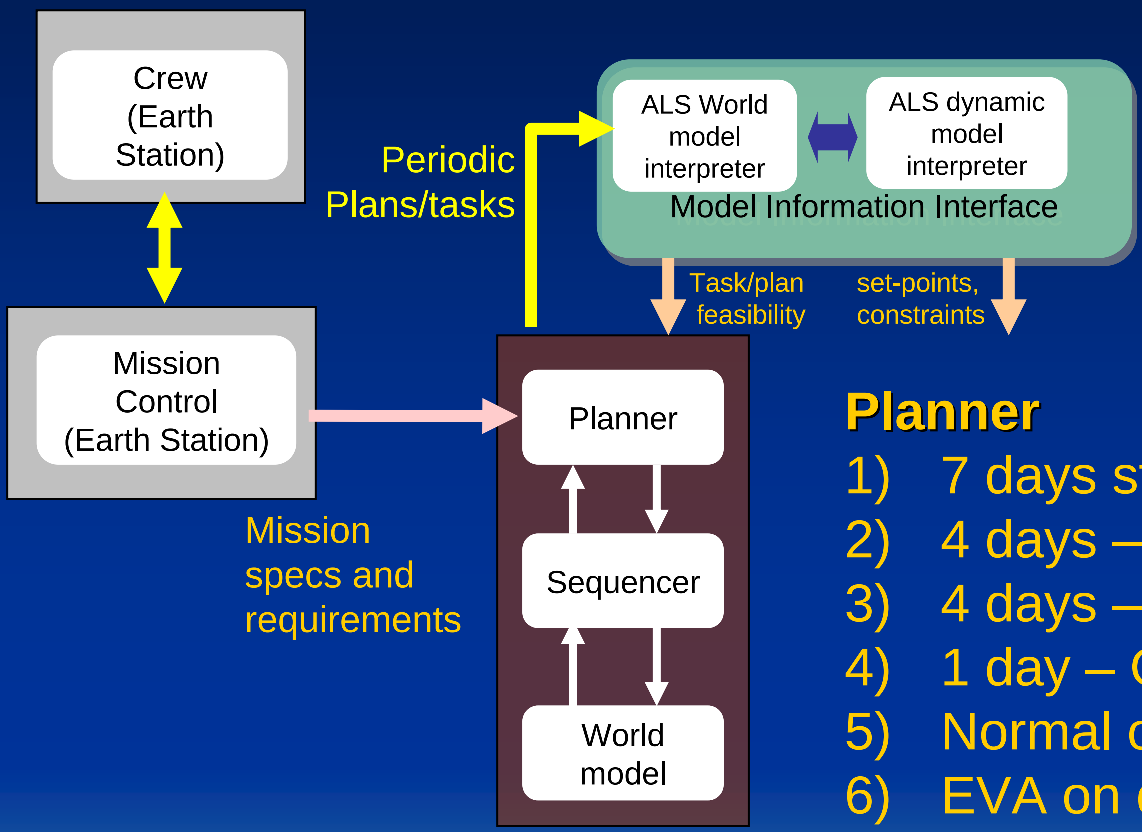


Example: Planning + Control



- 90 day mission with 28 day cycles
- Phase 1:
  - Startup
  - EVA on day 18
- First generate 28 day plan
  - Initialization + testing activities
  - Science expts. startup
  - Build up buffers to required levels

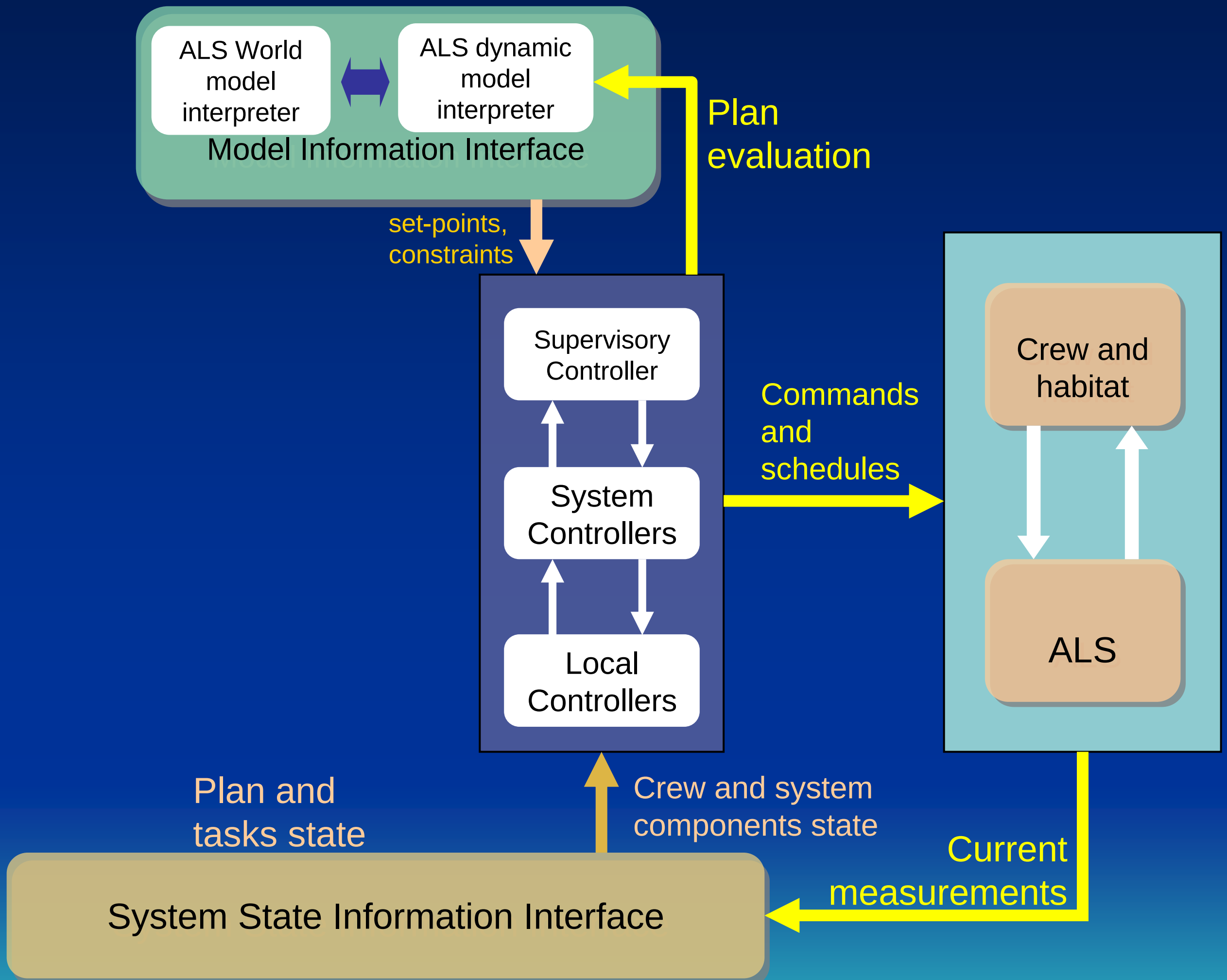
Example: Planning + Control



Planner

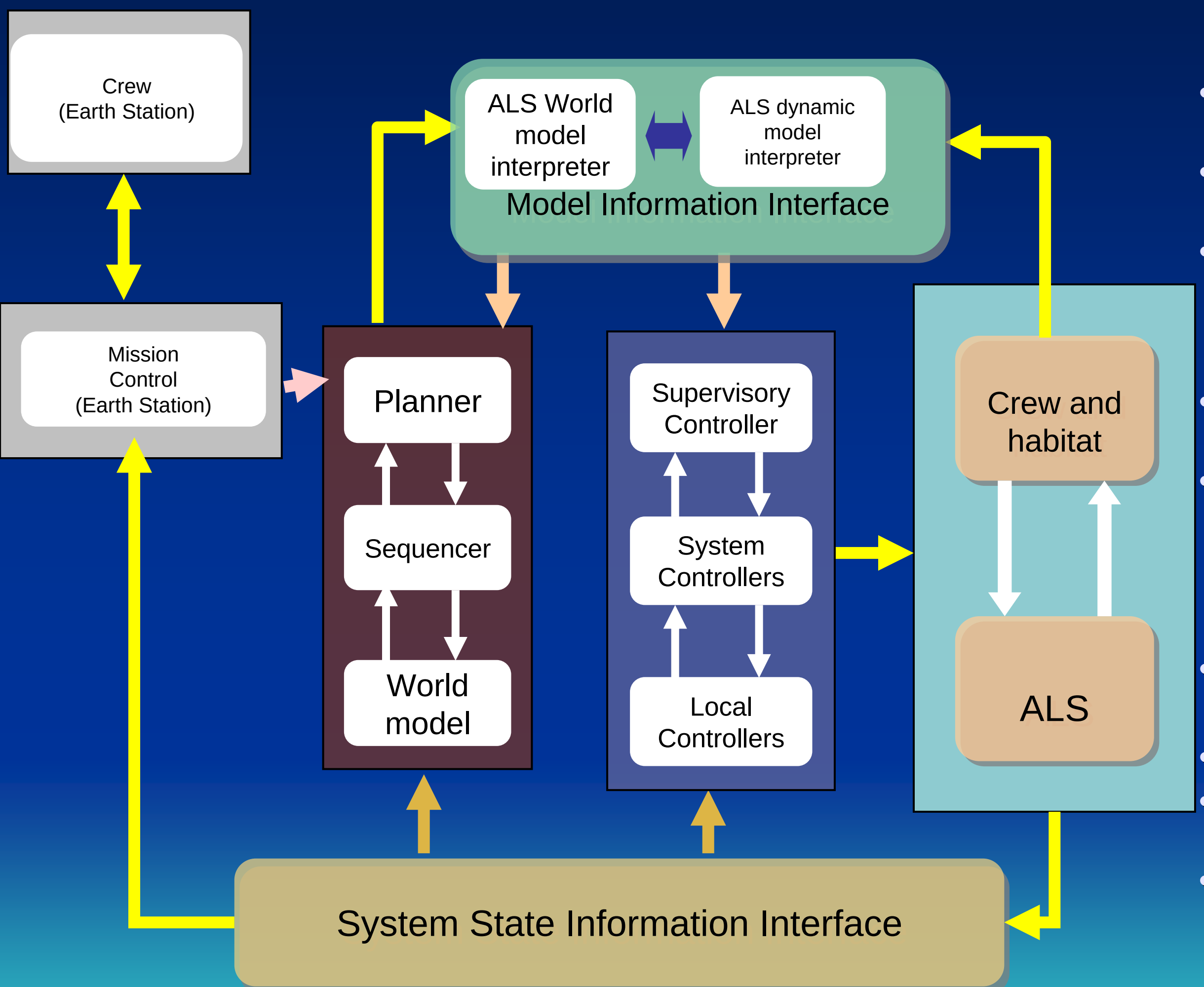
1) 7 days startup
2) 4 days – high CO_2 consumption
3) 4 days – high CO_2 state to scrub system
4) 1 day – O_2 preparation for EVA
5) Normal operations from day 10
6) EVA on day 18
7) Maintenance checks day 19-20
8) Normal operations day 20-28

Example: Planning + Control



Dynamic Control Executive Takes Over

Example: continued



- Day 10 – Anomaly detection & analysis: Restriction in CO_2 output from CDRA + leak in dessicant bed
- Controller: Restrict CRS + OGS operations
- Report to Planner -- CO_2 clear up needs to 5 days
- Question:
  - (i) perform 2 day CDRA repair – creates O_2 restriction
  - (ii) push EVA from cycle to day 20
- **Mission control + crew – cannot push back EVA**
- **Planner + Controller solution:**
  - **Crew give up exercise period – from day 9 to 20**
  - **EVA on day 18**
  - **CDRA repair days 19 & 20**
- **Repair procedures chosen by sequencer**
- **System state, models updated**
- **Planner suggests return to normal ops**
- **Controller concurs**

Issues in ISHM & System design

- ISHM does not (just) imply autonomy – ISHM has an important role in humans-in-the loop systems (crew, mission control)
  - Apollo 13 scenario – faster response
- ISHM is not just to deal with failures – it should be maintaining and optimizing nominal + degraded operations
  - Resource allocation
  - Reduction in mission costs (ESM)
- An Approach: Simulation test-beds that are based on systematic modeling technologies
  - Contribute to more efficient, reliable, and safe design
  - Address system integration issues (hardware–hardware, hardware–software)
  - Tools for “what-if” (scenario) analysis
  - Variety of other analysis tools that can be used by mission controllers and crew during missions

Focus: Decision Support first and primary; Autonomy secondary

Current and Future Applications

- Crew Exploration Vehicle
  - Air, Water, Waste & Power systems – does not have to be completely closed-loop
  - Other subsystems of the CEV
  - Deal with partial shut down during uncrewed operations (e.g., while crew on lunar surface) and startup
- Lunar Habitats
  - Move toward closed loop air and water
  - Resource monitoring important: link to scheduling and operations
- Mars Vehicles and Habitats
  - All components including biomass systems important
  - Closed loop operations
  - Resource and health monitoring, scheduling, predictive analysis, control, maintenance, and prognosis will be key to success of such missions

Number of design and run-time metrics will have to be addressed

One of the more important ones – Equivalent System Mass (ESM)